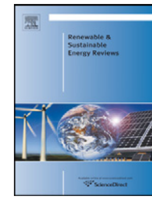
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Operation challenges for fast-growing China's hydropower systems and respondence to energy saving and emission reduction

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A B S T R A C T

During the past two decades, in particular the past decade, there has been a rapid rate of development of hydropower in China. It is foreseeable that the same rate of development will be maintained in the next decade. The total installed generation capacity of hydropower in China has now surpassed 200 GW and ranks first in the world. The unprecedented rate of expansion, development scale, emergence of large number of hydro plants with high head and huge capacity, and electric power transmission have led to significant changes in management and operation of large-scale hydropower systems which have become one of the significant factors in constraining the security and economic operation of power grid in China. This article gives an overview of the China's hydropower, analyses the new challenges that it faces, highlights the key scientific and technological issues that need to be solved, and pinpoints that the solution of these problems will be the key to the realization of energy saving and emission reduction by China in 2020.

Contents

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1. Introduction

Hydropower's low cost, near-zero pollution emissions and ability to quickly respond to peak loads make it a valuable energy source. In past years, hydropower occupied about 15% of Chinese total electricity generation and about 22% of total installed capacity. Now it is the most widely used renewable resource for electric power generation in the China. According to the proposed "Twelve 'Five Year' Electrical Plan in China" that will be released soon, hydropower will be placed in the first priority amongst all types of development of electricity generation and it is recognized as the most stable and reliable approach to reduce the proportion of non-fossil energy to one-time energy consumption in China to 15% in 2020 and 40–45% carbon emission.

Up to the end of 2010, 213.4 GW of hydropower generation capacity in China, with approximately 22.2% of total generation capacity, has been reached, which is the result of rapid development of hydropower and power grid during the past two decades, in particular the past decade. It is foreseeable that the same rate of development will be maintained in the next decade. The hydropower installed capacity will reach 330 GW in 2020. More than 45,000 hydropower plants exist in China, which include about 400 ones with more than 50 MW generation capacity, 85 ones with more than 300 MW and 32 ones with more than 1000 MW. The largest hydropower plant in the world, the Three Gorges with the total capacity of 22.4 GW and an annual production of 84.7 trillion Wh, is a typical example.

At present, the total generation capacity has reached 962.19 GW in China, about 73.4% of generation capacity is from thermal power plants, 22.2% from hydropower plants, a very small percentage from other energy. About 70% thermal plants are using coal for electric power generation in China. However, about 82 of coal deposits are concentrated in the north and southwest regions. About 70% of hydro resources are in 5 southwestern provinces, cities or autonomous regions, including Sichuan, Yunnan, Tibet, Guizhou, Chongqing, and Guangxi. However, the majority of electricity consumption is required in the eastern and the southern coastal regions as well as some part of the central region. Long distance and large scale electric power transmission is necessary for effective utilization of hydropower resources. In the past 10 years, the total length of high-voltage transmission lines of 35 kV and above increased by 69%, and total substation storages increased by 2.3 fold. 750 kV UHV AC, 1000 kV UHV AC and ±800 kV UHV DC have been put into operation successfully. By the end of 2009, the total length of high-voltage transmission lines of 220 kV reached 399,400 km. Now, most of regions are connected by interconnected national grids. The power systems of China have the capacity of transporting a massive amount of electricity over the geographic span of huge country. The operation and management of hydropower systems in China are characterized by large scale, trans-basin, trans-province, and trans-region. The operation and management of large-scale hydropower systems have become one of the significant factors in constraining the security and economic operation of power grid in China. The challenges to the operation management of the large scale hydropower systems are tremendous. New problems, which have direct impacts and relations to the attainable efficiency of the hydropower systems comprising the commissioned plants as well as those large-scale plants under construction, have emerged and become the technical bottleneck in operation and management of systems of hydropower stations in China.

2. An overview of China's hydropower

China is endowed with large hydro potential. The exploitable hydro capacity is 542 GW and the corresponding annual generating production 2470 trillion Wh, ranked first in the world. The development process of hydropower in China has lasted for 100 years or so. Tables 1 and 2 respectively list the top 20 countries in the world in terms of total installed capacity of hydropower and generation by the end of 2007. The two tables show that China ranked first from both two indexes. Table 3 shows the total installed

Table 1
Ranking of country (top 20 in the world) in terms of hydropower installed capacity (2007, unit: GW).

Rank	Country	Capacity (GW)	Rank	Country	Capacity (GW)
1	China	145.26	11	Venezuela	14.597
2	USA	77.885	12	Italy	13.573
3	Brazil	76.871	13	Switzerland	13.465
4	Canada	73.439	14	Turkey	13.395
5	Russia	46.062	15	Mexico	13.143
6	India	35.209	16	Spain	13.025
7	Norway	27.832	17	Argentina	9.94
8	Japan	21.824	18	Columbia	8.525
9	France	20.829	19	Austria	8.429
10	Sweden	16.592	20	Paraguay	8.13

Table 2
Ranking of country (top 20 in the world) in terms of hydropower generation (2007, unit: trillion Wh).

Rank	Country	Generation	Rank	Country	Generation
1	China	486.7	11	France	57.6
2	Brazil	370.3	12	Paraguay	53.2
3	Canada	364.7	13	Columbia	41.4
4	USA	247.5	14	Austria	35.6
5	Russia	175.3	15	Turkey	35.5
6	Norway	132.6	16	Switzerland	34.9
7	India	122.6	17	Italy	32.5
8	Venezuela	83.0	18	Argentina	30.2
9	Japan	73.3	19	Vietnam	29.6
10	Sweden	65.5	20	Pakistan	28.4

Table 3
Total hydropower installed capacity in GW and generation in trillion Wh.

Year	Capacity	Annual generation	Year	Capacity	Annual Generation
1949	0.36	1.20	1980	2031.8	58.21
1950	0.36	1.32	1981	21.93	65.55
1951	0.38	1.49	1982	22.96	74.40
1952	0.39	1.83	1983	24.17	86.36
1953	0.53	2.55	1984	25.60	86.78
1954	0.61	3.20	1985	26.42	92.37
1955	0.70	3.40	1986	27.54	94.48
1956	0.91	4.71	1987	30.19	100.23
1957	1.02	4.82	1988	32.70	109.18
1958	1.22	4.11	1989	34.58	118.45
1959	1.62	4.36	1990	36.05	126.35
1960	1.94	7.41	1991	37.88	124.84
1961	2.33	7.41	1992	40.68	131.47
1962	2.38	9.04	1993	44.89	151.60
1963	2.43	8.69	1994	49.06	166.79
1964	2.68	10.60	1995	52.18	186.77
1965	3.02	10.41	1996	55.58	186.92
1966	3.64	12.62	1997	59.73	194.56
1967	3.84	13.14	1998	65.07	204.30
1968	4.39	11.50	1999	72.97	212.93
1969	5.05	16.01	2000	79.35	243.13
1970	6.24	20.46	2001	83.01	261.11
1971	7.80	25.06	2002	86.07	274.57
1972	8.70	28.82	2003	94.90	281.33
1973	10.30	38.90	2004	105.24	330.99
1974	11.82	41.44	2005	117.39	396.40
1975	13.43	47.63	2006	128.57	416.70
1976	14.66	45.64	2007	145.26	486.70
1977	15.77	47.65	2008	172.60	565.55
1978	17.28	44.63	2009	196.29	571.68
1979	19.11	50.12	2010	213.40	

capacity and generation of hydropower in China since 1949. The installed capacity has jumped more than 593% compared with 1949, and generation more than 476% (based on 2009 data). Specially, the average annual increment is more than 10 GW from 2003 whilst the annual increment in 2009 reached 23.69 GW, which is even more than the total installed capacity of Japan (rank number 8 in the world). Referred to the most recent data by the end of 2010, the hydropower installed capacity in China has reached 213.4 GW whose amount is 2.74 times that of the second ranked USA (based on 2007 data) (Table 1). However, the current proportion of hydropower in China is not high, i.e. only 37%, which is far less than over 80% in the western countries such as USA, France, Norway, etc.

According to the proposed "Twelve 'Five Year' Electrical Plan in China" that will be released soon, hydropower will be placed in the first priority amongst all types of development of electricity generation. Emphasis will be highlighted on the development of 6 hydropower bases scattered in the western region, i.e., Jinshajiang River, Yalongjiang River, Daduhe River, Lancangjiang River, Nujiang River and the upper main stream of Yellow River. Development will further be made towards basins in Tibet such as Yarlung Zangbo River. According to the aforementioned plan, the hydropower installed capacity will reach 284 GW and 330 GW in 2015 and 2020, respectively. It is projected that, in that time, the scale of hydropower installed capacity in China will be equivalent to the summation of hydropower installed capacities of the other top seven countries in the world (based on data of 2007 in Table 1). This rate of expansion and scale of construction are very rare in the world history. The challenges of operations and management of hydropower systems in China are tremendous and unique.

3. Characteristics of China's hydropower systems

More than 60% of hydropower resources in China are focused on the main stream of several largest rivers and they have been planned as 13 large hydropower bases [14]. Their total capacity of cascaded plants on the main stream of these largest rivers has been planned to reach 227.96 GW which occupies about 42% of the whole exploitable hydro capacity. The followings are the most distinct features of China's hydropower systems.

Super scale: We have mentioned above that the current capacity of hydropower is 2.74 times that of the second ranked USA. By the end of 2020, the scale of hydropower capacity in China will be equivalent to the summation of one of the other top seven countries in the world. Now, amongst the top ten hydro plants under construction or commission in the world, four of them are located in China. They are respectively the Three Gorges, Xiluodu, Xiangjiaba and Longtan, with the total capacity from 6.3 GW to 22.4 GW, ranked 1, 3, 7 and 9, respectively.

Huge unit: In recent decades, the unit generation capacity of hydro turbines in China has been steadily enhanced. The 300 MW, 400 MW and 550 MW of unit capacity have been widely used in recently developed projects in China. The Three Gorges project is a milestone that 700 MW of unit capacity of hydro turbine is first adopted. On its heels, other projects with huge capacity, such as the Longtan and Xiaowan, also adopted 700 MW of unit hydro turbine. Furthermore, 1000 MW and above of hydro turbines are being developed and will be employed by Xiluodu, Xiangjiaba and other new projects.

Large scale cascaded hydropower plants: There are a lot of hydroelectric power plants on the main stream of rivers in 13 hydro bases. Table 4 shows the generation information related to the 13 hydropower bases. The priority of developing hydropower is given to the Wujiang River, the Nanpanjiang–Hongshuihe River, the Yangtze River Upper Reaches, the Lancangjiang River, the

Table 4
General information of the 13 of largest hydropower bases in China.

Name	Capacity (GW)	Annual generation (trillion Wh)	Number of cascaded plants on the main stream
Jinshajiang	62.25	292	13
Yangtze River Upper Reaches	28.84	128	8
Yalongjiang	25.7	125	21
Lancangjiang	25.11	140	14
Daduhe	24.92	113.6	16
Nujiang	21.99	103.7	13
Yellow River Upper Reaches	20.93	75	16
Lanpangjiang–Hongshuihe	14.30	63.5	18
East Region[a]	13.26	35.5	
Fujian, Zhejiang and Jiangxi[a]	12.20	31.5	
Wujiang	11.22	39.6	11
West Hulan[a]	10.81	37.8	
Middle Yellow River	64.30	17.8	8
Summation	277.96	1203	

[a] An aggregative name that includes a lot of cascaded hydropower plants distributed in different basins. Correspondingly, their number of cascaded plants on the main stream is vacant.

Jinshajiang River, the Yalongjiang River, the Daluhe River and the Nujiang River in recent two decades or next decades. The total capacity of cascaded hydropower plants for the eight bases aforementioned varies from 11.22 GW to 62.25 GW, the total generation from 39.6 trillion Wh to 292 trillion Wh, and the number of cascaded plants from 8 to 21. Specifically, all hydroelectric power plants on the main stream of the Hongshuihe River and the Wujiang River have been developed and are being implemented into operation. The Three Gorges plant, being the largest hydroelectric plant in the world and one of the cascaded hydropower plants on the main stream of the Yangtze River Upper Reaches, has been put into production since 2008.

High-head: There are more than 100 developed and developing hydropower plants whose installed capacity is more than 1000 MW. This is contributed greatly by plants under development or in planning, most of which are of high head. Parts of them are above 100 m or even 200 m. Table 5 lists parts of plants whose installed capacity is more than 1000 MW and the highest head is above 100 m. Most plants are located in the Jinshajiang River, Yalongjiang River, Daduhe River, Lancangjiang River, Hongshuihe River and the upper main stream of Yellow River that are the priority of hydropower development in the past two decades and the future.

Long-distance of electric power transmission: As mentioned above, most of the energy resources are in the western and northern regions, whereas the majority of electricity consumption is required in the eastern and the southern coastal regions as well as some part of the central region. Hence, a national strategy of electricity transmission from western to eastern China has been formulated. One of the main objectives of the strategy is thus to exploit the abundant hydro-power resources in Guizhou, Yunnan and Sichuan provinces and transfer electricity eastward to southern, central and northern China. The economically prosperous eastern areas, such Shanghai, Jiangsu, Zhejiang, Beijing, Tianjin will be benefited from the project. There are three transmission corridors from the west to east. Two corridors are related to hydropower energy transmission. The central corridor is to transmit power from hydro plants including the Three Gorges and Xiluodu along Jinshangjiang River to central and eastern China via both AC and DC lines. The southern corridor will transmit the hydropower distributed in the Lancanjiang River, Hongshuihe River, Wujiang River and Nujiang River in the Yunnan, Guizhou and Guangxi provinces and the thermal power in the Guizhou province to the Guangdong

Table 5
Part of hydroelectric plants whose capacity is over 1000 MW.

Name of Base	Plant	Capacity (MW)	Annual generation (trillion Wh)	Turbine (MW) (capacity × units)	Highest head (m)
Jinshajiang	Jinanqiao	2400	9.23	600 × 4	120
Jinshajiang	Guanyinyan	3000	10.60	600 × 5	117
Jinshajiang	Wudongde	8700	31.74	870 × 10	130
Jinshajiang	Baihetan	1400	49.53	875 × 16	220
Jinshajiang	Xiluodu	13,860	57.12	770 × 18	220
Jinshajiang	Xiangjiaba	6400	28.88	800 × 8	113
Yangtze River Upper Reaches	Three Gorges	22,600	84.70	700 × 32	113
Yalongjiang	Lianghekou	3000	11.69	500 × 6	278
Yalongjiang	Jinping-I	3600	17.40	600 × 6	233
Yalongjiang	Jinping-II	4800	21.08	600 × 8	317
Yalongjiang	Guandi	2400	8.71	600 × 4	124
Yalongjiang	Ertan	3300	17.00	550 × 6	185
Daduhe	Pubugou	3300	14.58	550 × 6	178
Wujiang	Wujiangdu	1250	4.06	250 × 5	131
Wujiang	Goupitan	3045	9.35	609 × 5	200
Yangtze River Upper Reaches	Shuibuya	1600	3.92	400 × 4	203
Yangtze River Upper Reaches	Geheyan	1200	3.04	300 × 4	121.5
Yellow River Upper Reaches	Laxiwa	4200	10.22	700 × 6	220
Yellow River Upper Reaches	Lijiaxia	2000	6.06	400 × 5	135.6
Yellow River Upper Reaches	Gongbaixia	1500	5.14	300 × 5	106.6
Hongshuihe	Tianshengqiao-I	1200	5.15	300 × 4	143
Hongshuihe	Tianshengqiao-II	1320	8.20	220 × 6	204
Hongshuihe	Longtan	6300	15.67	700 × 9	179
Nanpanjiang	Guangzhao	1040	2.70	260 × 4	165
Lancangjiang	Gushui	2600	10.52	650 × 4	261
Lancangjiang	Wulonglong	1200	4.51	400 × 3	126
Lancangjiang	Huangden	1600	6.62	400 × 4	142
Lancangjiang	Xiaowan	4320	19.81	720 × 6	251
Lancangjiang	Manwan	1670	7.78	300 × 1 + 250 × 5 +120 × 1	100
Lancangjiang	Luozhadu	5850	23.91	650 × 9	215

province in Southern China. The project has speeded up the links of the entire power system in China.

4. Relationship with energy-saving and emission reduction

Generally, reservoirs (hydroelectric plants) can be served for the multiple goals of electricity generation, flood control, water supply, irrigation, ecology, environment, navigation, etc. The main objectives of operation and management of hydropower systems are to determine the optimal hydro generation that satisfies various complicated constraints including power grid security, environmental protection, energy saving, economical operation, and so on.

Owing to the uneven spatial and temporal distribution of runoff and varying comprehensive demands of electricity generation, water supply and other usages, the optimal operation of hydropower systems can be classified into various scales, i.e., long-term, mid-term, short-term and real-time, which are all complicated tasks. The complexity of optimal operation of hydropower system mainly lies on the uncertainty of runoff and electricity loads. Under the present scientific and technological level, water flow process and electricity loads cannot be accurately predicted. The problem of optimal operation of hydropower systems has not been resolved satisfactorily.

Research on optimal operation for hydropower system began in 1940s [11]. The strong influence of operational research theory and computer science technologies in the area can be observed. A big leap in this topic came in 1950s and 1960s. It entered into the golden development stage in 1970s and 1980s [19–21]. Following more than 70 years' effort, many research and application outcomes were proposed, mainly comprising linear programming, non-linear programming, dynamic programming, Lagrangian relaxation, network flow method, large-scale system decomposition-coordination, etc. [16,17,1,21,13]. Since 1990s, various artificial intelligence algorithms, such as artificial neural networks, simulated annealing algorithm, genetic algorithm, chaos optimization algorithm, ant colony algorithm, particle swarm optimization algorithm, etc., have been applied to optimal operation of hydropower (reservoir) systems [15,5,6,8,9,10,12,18].

It is widely recognized that the optimal operation of hydrothermal systems is an important approach to reduce the utility of fossil fuels by substantially improving efficiency in a mixed power system [23,24]. Currently, the energy sources of power grids in China are mainly constituted by hydropower and thermal power. With the increasing occurrence of global warming and extreme climate, the difference between peak and valley becomes bigger and bigger, which in turn poses difficulties on peak regulation of most power grids. There is a pressing need to enhance the composition of energy sources in power grids and to introduce high quality hydropower resources. On the other hand, with the heavy national investment on new energy sources such as wind energy and solar energy, problems arise on how to absorb these new energy sources through the installation of pumped-storage power plants and their joint operation with hydropower systems. Many previous local and international research and application studies demonstrated that optimal operation of hydropower systems via rational scientific methods can increase power generation of systems of cascade hydropower systems by 1.5–15% [2]. According to our experiences, taking the power grids at South-Western regions of China with higher proportion of hydropower as an example, the potential increase of power generation via the regional grid platform will be even more and will exceed 15%. Even if a conservative value of 1.5% is taken, for the annual national electricity generating capacity of 571.68 billion kWh in 2009, an increase of 8.58 billion kWh will be attained. It exceeds one-tenth of the annual design electricity generating value of the Three Gorges which is 84.7 billion kWh. A saving of 3.432 million tonnes of standard coal and a reduction of carbon dioxide emission of 855.4 tonnes can be accomplished. The effect on energy-saving and emission reduction will be quite substantial.

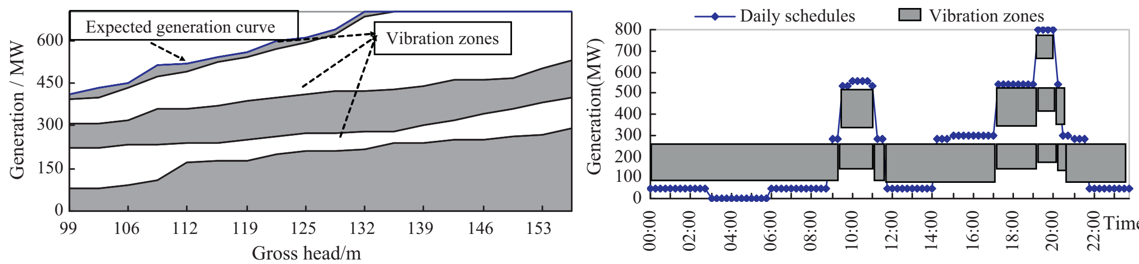


Fig. 1. Problem of multi-vibration zones with huge capacity and high head.

5. New challenges facing optimal operation of hydropower in China

5.1. Multi-level coordination problem for large-scale hydropower energy transmission

Currently, hydropower resources are mainly concentrated in economically underdeveloped southwestern China whilst the major electricity load is around Yangtze River delta and Pearl River delta. In order to cater for this unbalanced energy structure, the strategic plan of "transmission of electricity from the west to the east" was fully implemented in 2000, with the construction of main hydropower works around Three Gorges and Longtan. This, together with the construction of the ultra-high voltage transmission grid during the past decade, basically realizes nationwide power network connection. The connections in Southwestern China, Southern China, Eastern China and Central China together constitute the largest hydropower and electricity network system in the world. Through the power system reform, the electrical industry is now developed into a multi-level hydropower operation and management system. The national, regional, provincial, and local control centres (substations) are responsible for the balance and coordination of electricity resources amongst regional, inter-provincial, and intra-provincial power grids, respectively. The key characteristics of the operation of hydropower system in China are large-scale, large areal extent, long distance, trans-region, trans-province, and trans-basin. It is an extremely complicated optimal operation and management problem.

5.2. Operation problem on the multiple vibration zones for plants with huge capacity and high head in large-scale cascaded hydropower system

Many dams in the main stem of several large rivers in Southwestern China are more than 100 m high. Even those with 200–300 m high are not rare. The installed capacity of a single plant and a cascade hydropower system can be very large and shoulder a more complicated optimal operation task. The unit vibration zones have great effect on the security of hydropower plant and power grids [3,22]. Generally, the vibration zone is closely related to the generating water head, power output and power generating flow. If, during the continuous operation process of the station, the power output exceeds the specified range, it will pass through multi-vibration zones and will have related impact on its operation during subsequent periods. In such cases, it may sometimes be difficult to determine an appropriate regulation mode and may aggravate the difficulties on optimal operation of hydropower plant. If multi-vibration zones exist simultaneously in several downstream cascade hydropower stations, it will be even more difficult to determine a feasible unit generator commitment within a limited range of period. From mathematical point of view, it is a multi-dimensional discontinuous optimization problem and cannot be solved by conventional optimization techniques. Novel techniques are entailed for its solution.

Fig. 1 is a practical example about multiple vibration zones for the Longtan plant with huge capacity and high head. The Longtan plant is the largest one in the Hongshui River, with 9 generators of 700 MW each and total capability of 6.3 GW. Three vibration zones exist for each generator. Dynamic variation of the generating water head often happens for regulating system loads. Frequently, a variation of water head of 1–2 m may trigger variation in the unit vibration zone. In some cases, several vibration zones may be surpassed and may have mutual influence between different time periods. For the Longtan plant, there are two upper hydropower plants, i.e., the Upper Tianshengqiao plant, and the Lower Tianshengqiao plant and multiple vibration zones also exist for them. The operations for the cascaded hydropower system will be more complicated because of the hydraulic connection between the upstream and downstream. The multi-vibration zones with huge capacity and high head are a distinct operation problem of large quantity of large-scale cascade hydropower systems in commission and to be commissioned soon in China. The left side of Fig. 1 shows the unit vibration zone of Longtan Hydropower plant whilst the right side of Fig. 1 represents a real case of planned operation in the Upper Tianshengqiao plant. It can be observed that from the figure that, during the operation process, the unit needs to surpass several vibration zones, which becomes an inevitable problem.

5.3. Problem of peak regulation of hydropower in multi-power grids

Following the extension of the scale of hydropower and power grid, the system networks will impose a more distinct need on peak regulation, frequency regulation and emergency reserve of hydropower plants. The operations and management of large-scale hydropower systems will be completely different from the medium or small ones built previously. An obvious change to the operation modes of single hydropower plants and hydropower systems is the emergent demand for peak regulations for multiple grids. The problems include electricity transmission to different provincial power grids by plants located at upstream and downstream of the same river, as well as that by a single hydropower plant to several provincial power grids. Fig. 2 shows a case example of electricity transmission by cascaded hydropower system in the Hongshui River. The distribution of electricity includes 4 provinces, i.e., Yunnan, Guizhou, Guangdong and Guangxi. The Yunpeng and Lubuge plants at the upstream convey electricity to Yunnan whilst Guangzhao and Dongqing plants provide power to Guizhou. The Upper and Lower Tianshengqiao plants and Longtan plant convey electricity to Guangdong and Guangxi simultaneously whilst other plants at the main stream and tributaries are mainly responsible to provide electricity to Guangxi. The total power load, peak, and difference between peak and valley at different receiving power grids are quite different, which can be up to a few folds. The load variation and periods of peak and valley may not be consistent. Whilst

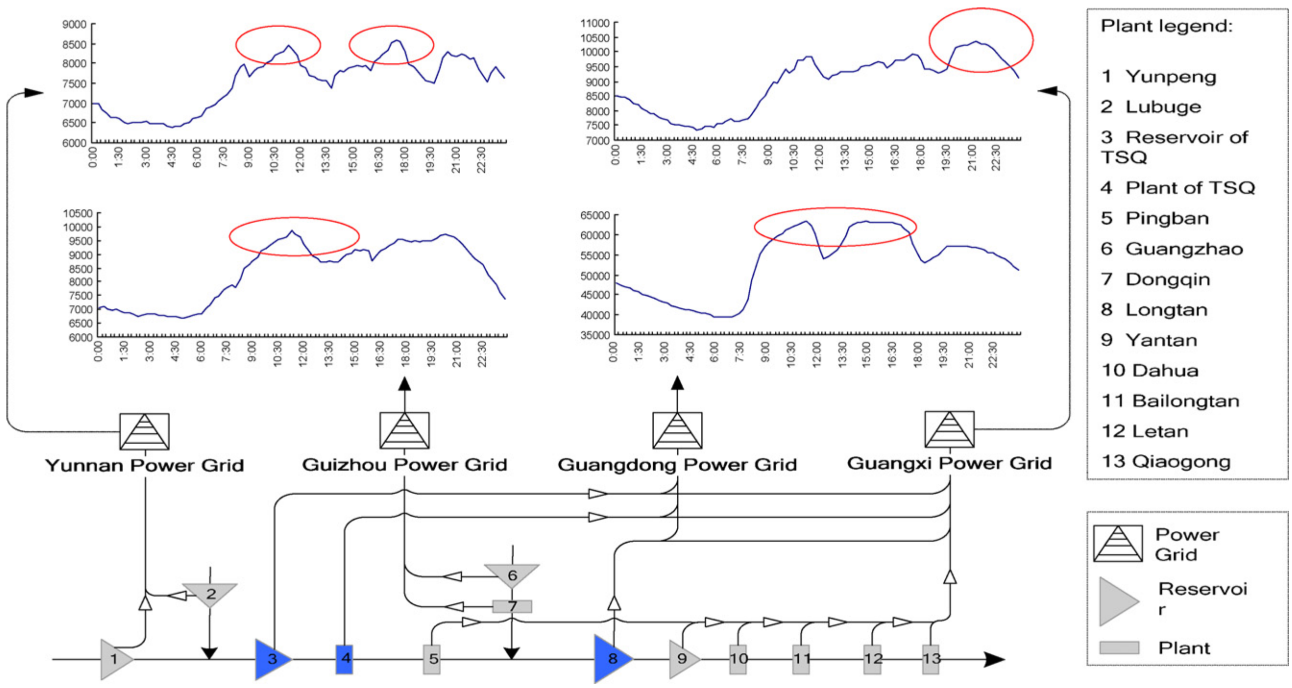


Fig. 2. An example of peak regulation under multi-power grids.

hydropower plants in the river basin have intimate hydraulic connections, they also have mutually related as well as conflicting power connections. The complicated application demands of various power grids need to be considered in short-term peak regulation of hydropower systems. This is substantially different from the peak regulation problem for hydropower systems under a single power grid.

5.4. Impact of extreme climate on safe operation of hydropower and power grids

At present, the structure of energy sources in China mainly relies on thermal and hydropower: thermal installed capacity occupies 74.6%, hydropower occupies 22.5%, and other energy sources including nuclear, wind, solar, etc. occupy 2.9%. It is anticipated that, after 2020, the proportion of hydropower installed capacity in the Southern provincial power grids, such as Yunnan and Sichuan, will occupy more than 70% inside the region itself. The Southern China power grid, with the highest proportion of hydropower, has a potential hydropower capacity of 148 GW and occupies 27% of the country. It is forecasted that its hydropower installed capacity will be increased from the current 48.5 GW to 100 GW in 2015, the corresponding proportion inside the grid from 33% to 38%, and the corresponding proportion of total hydropower installed capacity within the nation from 25% to 38%. As the scale of the hydropower becomes larger and larger, the impact of uncertain runoff quantity on hydropower and power grids will become more significant. The impact of the extreme climate on the operation of hydropower stations will be even more. The drought at southwestern region of the country in 2008 exhibits an important warning.

5.5. Problem on solution of hydropower systems and operating efficiency

The rate of expansion and scale of construction of hydropower in China are unprecedented in the world history. On the other hand, the operations of hydropower systems involve a complicated set of constraints, in particular a large amount of spatiotemporal coupling constraints. As an example, the multiple vibration zones for plants with huge capacity are in fact a complicated practical need. With the more refined operations and management of power grid, the demands for peak regulation, generation, release and level of hydropower plants are becoming higher. For instance, for plants with better regulation capability and higher installed capacity, there are mandatory demands on partitioning of peak regulation, depth of peak regulation, variation of unit power output. The power output is then specified certain fixed value and the depth of peak regulation should be consistent to the variation of power load curve. Another example is the demand on some plants to adopt or refer to previous scheme of real operation, in accordance with real engineering practice. Other example such as electricity transmission constraints on sectional area and output limit of transmission channels amongst power grids, based on security and safety reasons, will also impose higher demand on hydropower operations. Hence, the operations of hydropower systems are the optimal problems with high-dimensional, nonlinearity, multi-stage, stringent constraints. The ever expansion of hydropower systems render hydraulic and electricity connections amongst plants and cascaded systems more complicated. The engineering practical needs impose a more complicated and difficult solution to the refinement demands of the optimal operation. The computation effort and time during the solution process will increase with the number of plants and number of constraints. It is crucial to ensure the solution efficiency and quality of large-scale hydropower system so that the optimization results can be applied to suit engineering practical needs. There are strong demands on novel methods and techniques in order to solve these problems.

6. Key scientific and technical problems to be solved

6.1. Modelling large-scale complicated hydropower systems

Reservoir (hydropower) systems involve power generation, flood control, water supply, irrigation, ecology and other comprehensive purposes [5,6]. During recent six decades, optimal operations of hydropower systems have been addressed by many

researches [21,2,15]. It is most popular from 1970s to 1990s, with the development of various models including linear programming, non-linear programming, dynamic programming, network flow programming, large-scale system decomposition, etc. During the past two decades, artificial intelligent algorithms, such as artificial neural network, genetic algorithm, ant colony optimization, were also applied. Dynamic programming was the most popular optimization technique in hydropower system. Amongst them, incremental dynamic programming (IDP), discrete differential dynamic programming (DDDP), incremental dynamic programming successive approximation (IDPSA), differential dynamic programming (DDP), progressive optimality algorithm (POA) and dynamic analytical (DA) method, which are employed to address the curse of dimensionality, are studied and applied extensively. However, on the whole, these methods have some drawbacks and the curse of dimensionality was not totally solved. There are two strategies to enhance the original dynamic programming. The first strategy is to reduce the number of state discretization, which occurs in IDP, DDDP and IDPSA. The overall concept is the successive iteration approximation. Each iteration is searched within a limited range of state-space. Another strategy is to replace discretization of state variable with certain analytical iterative solution, which is adopted by DDP, POA and DA. Hence, in order to pinpoint the current and prospective large-scale hydropower systems, the key scientific problem needed to be solved is to propose a general, practical and quick optimization method in order to address different optimization objectives, complicated security and operating constraints, spatial–temporal hydraulic and electricity connections during the optimization process, etc.

6.2. Parallel computation of optimal operation of hydropower systems

For large scale and complicated hydropower systems, the computation efficiency not only affects the feasibility, but also determines the utilization of the method. It is particularly true for short-term and real-time optimal operation. For complicated and large-scale optimal operation problems such as the hydropower systems, an effective way is to employ parallel computation in the solution process for enhancement of the solution speed and efficiency [7]. For hydropower system in region-oriented or provincial power grid, the attribute of natural spatial distribution of stations and the coordination management of optimal operation of intra-regional and inter-regional power systems are suitable for the solution by the parallel computation. Hence the introduction of the parallel computation to optimal operation analysis of hydropower system is a feasible and practical way to enhance the solution efficiency problem of complicated hydropower system.

6.3. Knowledge management of optimal operation of hydropower system

It will be a complicated task to build models for large scale hydropower systems. With the ever expansion of the scale of hydropower systems, more factors have to be considered so that the complexity and difficulty of model construction will be escalated in a non-linear manner. For operation problem of hydropower systems with strong engineering attributes, adequate simplifications are useful and necessary in order to enhance the solution efficiency and feasibility of the system. During the past decade, it is feasible to introduce intelligent techniques, such as knowledge management, for large-scale complicated models [4]. This technique is able to make induction based on the existing engineering knowledge, to depict and systemize the model construction process employing knowledge representation technique, to automatically direct the model construction and thus to facilitate the solution of complicated engineering problems.

6.4. Uncertainty analysis of optimal operation of hydropower system

The uncertainty of runoff is the key factor affecting the feasibility of any hydropower system scheduling, in particular for mid- to long-term optimal operation of power system. The occurrences of more frequent extreme climate in recent years also aggravate the difficulties of operation and management of hydropower systems. An important research direction remains to predict runoff of various scales, to enhance the prediction accuracy and forecast period, and to develop theory on uncertainty analysis of optimal operation of hydropower system based on uncertain runoff values at different confidence levels.

7. Conclusions

Hydropower is currently the largest renewable energy resources in China. It is the key to attain the target to reduce the proportion of non-fossil energy to one-time energy consumption in China to 15% in 2020. In order to accomplish this goal, it not only requires continuing substantial development of hydropower, but also needs to investigate emerging new problems on optimal operation and management of hydropower systems of ever-increasing scales. The objective is to furnish more effective scientific methods and decision-support tools to support the operation and management of current and prospective large-scale hydropower systems in China.

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References

[1] Allen RB, Bridgeman SG. Dynamic programming in hydropower scheduling. Journal of Water Resources Planning and Management-ASCE 1986;112(3):339–53.
[2] Barros MTL, Tsai FTC, Yang SL, Lopes JEG, Yeh WWG. Optimization of large-scale hydropower system operations. Journal of Water Resources Planning and Management-ASCE 2003;129(3):178–883.
[3] Catalao JPS, Mariano SJPS, Mendes VMF, Ferreira LAFM. Scheduling of head-sensitive cascaded hydro systems: a nonlinear approach. IEEE Transactions on Power Systems 2009;24:337–46.
[4] Chau KW, Chuntian Cheng, Li CW. Knowledge management system on flow and water quality modeling. Expert Systems with Applications 2002;22(4):321–30.
[5] Cheng C. Fuzzy optimal model for the flood control system of upper and middle reaches of the Yangtze River. Hydrological Sciences Journal 1999;44(4):573–82.
[6] Cheng C, Chau KW. Fuzzy iteration methodology for reservoir flood control operation. Journal of the American Water Resources Association 2001;37(5):1381–8.
[7] Cheng C, Wu X, Chau KW. Multiple criteria rainfall-runoff model calibration using a parallel genetic algorithm in a cluster of computer. Hydrological Sciences Journal 2005;50(6):1069–88.
[8] Cheng C, Wang W-C, Xu D-M, Chau KW. Optimizing hydropower reservoir operation using hybrid genetic algorithm and chaos. Water Resources Management 2008;22:895–909.
[9] Cheng C, Liao S, Wu X, Chau KW. Two stage particle swarm optimisation for long-term operation of a hydroelectric power system. The HKIE Transactions 2009;16(3):8–14.
[10] Cheng C, Liao S, Tang Z, Zhao M. Comparison of particle swarm optimization and dynamic programming for large scale hydro unit load dispatch. Energy Conversion and Management 2009;50(12):3007–14.
[11] EL-Hawary ME, Christensen GS. Optimal economic operation of electric power systems. New York/San Francisco/London: Academic Press; 1979.
[12] Fu Guangtao. A fuzzy optimization method for multicriteria decision making: an application to reservoir flood control operation. Expert Systems with Applications 2008;34(1):145–9.

[13] Howson HR, Sancho NGF. New algorithm for the solution of multi-state dynamic programming problems. Mathematical Programming 1975;8(1): 104–16.
[14] Huang H, Yan Z. Present situation and future prospect of hydropower in China. Renewable and Sustainable Energy Reviews 2009;13(6–7):1652–6.
[15] Labadie JW. Optimal operation of multireservoir systems: state-of-the-art review. Journal of Water Resources Planning and Management-ASCE 2004;130(2):93–111.
[16] Momoh JA, El-Hawary ME, Adapa R. A review of selected optimal power flow literature to 1993. Part I. Nonlinear and quadratic programming approaches. IEEE Transactions on Power Systems 1993;14(1):96–104.
[17] Momoh JA, El-Hawary ME, Adapa R. A review of selected optimal power flow literature to 1993. Part II. Newton, linear programming and interior point methods. IEEE Transactions on Power Systems 1993;14(1):105–11.
[18] Qin H, Zhou J, Lu Y, Wang Y, Zhang Y. Multi-objective differential evolution with adaptive Cauchy mutation for short-term multi-objective optimal hydro-thermal scheduling. Energy Conversion and Management 2010;51(4): 788–94.
[19] Simonovic SP. Reservoir systems analysis: closing gap between theory and practice. Journal of Water Resources Planning and Management 1992;118(3):262–80.
[20] Wurbs RA. Reservoir-system simulation and optimization models. Journal of Water Resources Planning and Management 1993;119(4):455–72.
[21] Yeh WW-G. Reservoir management and operations models: a state-of-the-art review. Water Resources Research 1985;21(12):1797–818.
[22] Yi JL, John W, Steven S. Dynamic optimal unit commitment and loading in hydropower systems. Journal of Water Resources Planning and Management-ASCE 2003;129(5):388–98.
[23] Yuksel I. Hydropower for sustainable water and energy development. Renewable and Sustainable Energy Reviews 2010;14(1):462–9.
[24] Yuksel I. As a renewable energy hydropower for sustainable development in Turkey. Renewable and Sustainable Energy Reviews 2010;14(9):3213–9.